

## **Wave-Induced Fluctuations in Underwater Light Field: Analysis of Data from RaDyO Experiments**

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### **LONG-TERM GOALS**

This project is part of the Radiance in a Dynamic Ocean (RaDyO) program which aims at developing an understanding of variability in underwater light field and its relation to dynamic processes within the ocean-atmosphere boundary layer.

### **OBJECTIVES**

We investigate fluctuations in underwater light field produced by sea surface waves under various boundary conditions. Our objectives focus on the characterization of wave-induced fluctuations in downwelling irradiance and radiance as a function of various environmental parameters and depth of observation. The central theme of our study is to characterize the most intense light fluctuations at shallow depths produced by surface wave focusing under sunny conditions. The focusing events occur in the form of high-amplitude short-duration pulses, which we refer to as light flashes.

The specific objectives of this project over the past year were to analyze field data collected during the RaDyO experiments carried out in 2008 and 2009 with special emphasis on the characterization of methodology for investigating wave-induced light fluctuations and probability distributions of instantaneous irradiance within the near-surface ocean under sunny conditions.

### **APPROACH**

As reported previously, we developed a special instrument, an Underwater Porcupine Radiometer System, which provides a capability to measure wave-induced fluctuations in downward irradiance and radiance with a high sampling frequency of 1 kHz. Our approach to field measurements involved the acquisition of time-series data of light fluctuations with the Porcupine system at various depths within the near-surface ocean, typically at depths from about 0.5 or 1 m to 10 m under sunny conditions. Typical 10-min time-series obtained with the Porcupine system using the sampling frequency of 1 kHz includes 600,000 data points for each of 23 light sensors of the system. Our approach in this project involves the use of various statistical methods for the analysis of these time-series data. These methods

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provide several statistical characteristics of light fluctuations such as statistical moments, probability density function, and spectral density function. Special methods of data analysis, referred to as a threshold-crossing analysis, are also used to provide the statistics describing the frequency and duration of wave-focusing events referred to as light flashes.

## WORK COMPLETED

We completed processing and quality control of all data of light fluctuations collected with the Porcupine instrument during three field experiments, the RaDyO experiments conducted from R/P FLIP in the Santa Barbara Channel and off Hawaii Islands, as well as our additional experiment conducted from the Aqua Alta Research Platform in the Adriatic Sea.

We completed analyses of data with focus on methodological issues associated with measurements and analysis of underwater light fluctuations and characterization of probability distributions of downward irradiance within the near-surface ocean under sunny conditions. These analyses resulted in the completion of two papers during the reporting period. Both papers have been accepted for publication in *Journal of Geophysical Research* (Darecki et al., in press; Gernez et al., in press).

We continue the analysis of our data, which is currently focused on the characterization of power spectra of irradiance fluctuations and statistical properties of light flashes caused by wave focusing.

## RESULTS

Our results show that the underwater light field within the near-surface ocean shows large fluctuations caused by focusing of sunlight by surface waves under sunny conditions. The downwelling light at near-surface depths can fluctuate greatly on times scales as short as milliseconds and spatial scales less than 1 cm. In the paper by Darecki et al. (in press) we demonstrate that specially designed radiometers, data acquisition systems, and sampling strategies are required to fully resolve the underwater effects of wave focusing and to ensure the adequacy of the collected data for the characterization of light fluctuations within the near-surface ocean under sunny conditions. Most importantly, these requirements pertain to resolving the shortest temporal scales ( $\sim 1 - 10$  ms) and the smallest spatial scales ( $\sim 1 - 5$  mm) of light fluctuations associated with wave focusing at near-surface depths. Typical commercial underwater radiometers that have been in common use in optical oceanography do not meet these requirements. Much of the past experimental work devoted to underwater light fluctuations did not satisfy these requirements either, and thus do not necessarily provide reliable data on fluctuations within the top few meters of the ocean under sunny conditions.

During the early phase of the RaDyO program we developed an Underwater Porcupine Radiometer System (Figure 1). The paper by Darecki et al. (in press) describes the Porcupine instrument and key aspects of the acquisition and processing of data obtained with this instrument. The distinctive features of the Porcupine instrument include multiple sensors for measuring the downward irradiance and radiance, a capability to properly resolve short temporal and small spatial scales of wave focusing at near-surface depths, and a capacity for acquiring high volumes of time-series data of light fluctuations. Representative example results of wave-induced light fluctuations obtained with the Porcupine instrument during field experiments as part of the RaDyO program are also presented. These results are used to support specific requirements of hardware design, data acquisition protocols, and

computational methods involved in data analysis. In particular, our results show that the irradiance collector of a few millimeters in diameter or smaller is required to provide adequate measurement of light flashes produced by wave focusing. The measurements with larger irradiance collectors can result in deceptive reduction of the measured intensity of fluctuations (Figure 2). The brightest flashes of irradiance or radiance can exceed the time-averaged irradiance or radiance by an order of magnitude and the duration of flashes is typically on the order of milliseconds to tens of milliseconds. The intensity of light fluctuations decreases rapidly with depth and is higher at longer light wavelengths compared with shorter wavelengths within the visible spectral range (Figure 3). The increase in wind speed beyond about  $5 \text{ m s}^{-1}$ , and hence an increase in the surface roughness, also result in the reduced intensity of light fluctuations.

Whereas the main focus of the paper by Darecki et al. (in press) is on the methodology of measurements and data analysis of wave-induced light fluctuations at near-surface depths under sunny conditions, the other paper by Gernez et al. [this issue] is focused on specific aspects of statistical analysis of data obtained with the Porcupine instrument under such conditions. This paper describes the first systematic study dedicated to the characterization of the probability distribution of instantaneous values of downward irradiance  $E_d(t)$  within the near-surface ocean when the sun is not covered by clouds. Our analysis of time-series data of wave-induced fluctuations in underwater downward irradiance within the green spectral band [ $E_d(t)$  at  $\lambda = 532 \text{ nm}$ ] collected at different depths under sunny conditions demonstrates large vertical changes in the probability distribution of instantaneous irradiance within the examined near-surface oceanic layer, i.e., from about 1 to 10 m (Figure 4). In the first few meters near the surface, the probability distribution of irradiance is highly skewed to the right and heavy-tailed. This is because of the occurrence of intense wave focusing events that exceed the mean irradiance,  $\overline{E}_d$ , several-fold or by tens of standard deviations. We tested several probability models, including log-normal, Gumbel, Fréchet, log-logistic, and Pareto, which were originally developed to describe skewed and heavy-tailed distributions. None of the models shows consistently good performance in terms of fitting the experimental distribution of irradiance over a broad range of values, especially within the right tail of the experimental distribution where the probability of relatively high irradiance values is less than 10%. This portion of the distribution corresponds approximately to light flashes with  $E_d > 1.5 \overline{E}_d$ , where  $\overline{E}_d$  is the time-averaged downward irradiance. We found, however, that the remaining part of the probability distribution covering all irradiance values smaller than the 90th percentile can be described with a reasonable accuracy (i.e., within 20%) with a log-normal model for all 86 measurements from the top 10 m of the ocean included in our analysis. This range of the distribution is approximately equivalent to irradiance values  $E_d < 1.5 \overline{E}_d$ .

The vertical changes in the probability distribution of irradiance are characterized by rapid decrease in the values of skewness and excess kurtosis with depth (Figure 5). Close to the surface at depths less than 1 m, these coefficients can assume values larger than 3 and 20, respectively. As the intensity of irradiance fluctuations decreases with depth, the probability distribution tends toward a function symmetrical around the mean like the normal probability distribution. At the 10 m depth, both the skewness and excess kurtosis are reduced to nearly zero, which is consistent with the normal distribution. This result suggests that the irradiance distribution approaches the Gaussian distribution with increasing depth. Such vertical changes can be attributed to an increasing role of diffuse light and a decreasing role of direct sunlight, which dampen irradiance fluctuations with depth.

## **IMPACT/APPLICATIONS**

The major impact of this project is to provide an understanding of wave-induced fluctuations in underwater light field. This phenomenon has been scantily investigated in the past. Our measurements and analyses provide critical information for achieving broader science goals of the RaDyO program, including the development of coupled surface wave-radiative transfer models. Our findings are also expected to have broader implications beyond the disciplines of ocean optics and physics, specifically in the areas of ocean biology and photochemistry.

## **RELATED PROJECTS**

This effort is related to our previous project funded under the RaDyO program and other projects supported by that program.

## **REFERENCES**

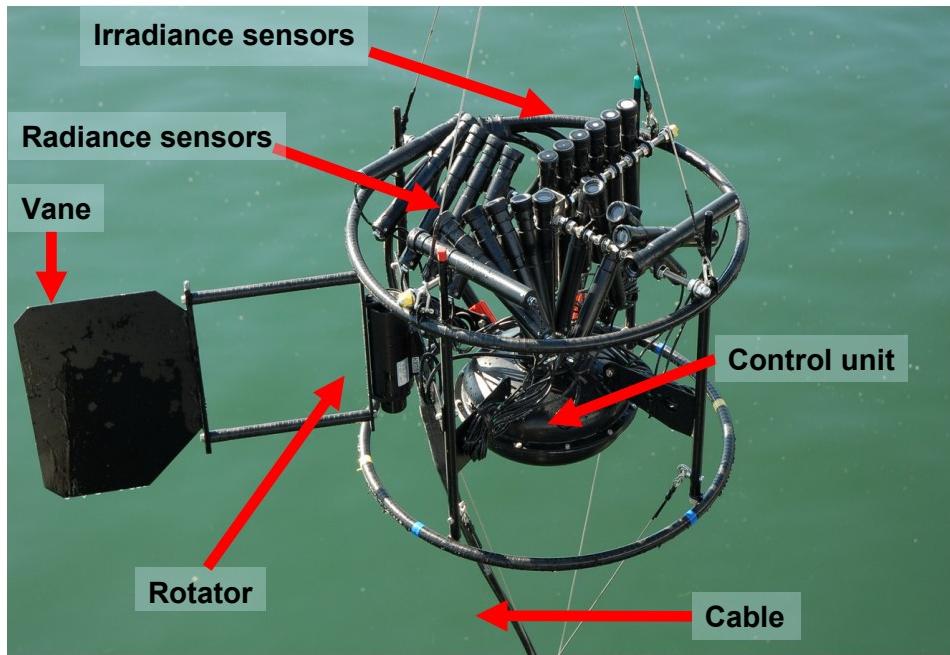
Darecki, M., D. Stramski, and M. Sokolski, Measurements of high-frequency light fluctuations induced by sea surface waves with an Underwater Porcupine Radiometer System, *J. Geophys. Res.*, doi:10.1029/2011JC007338, in press.

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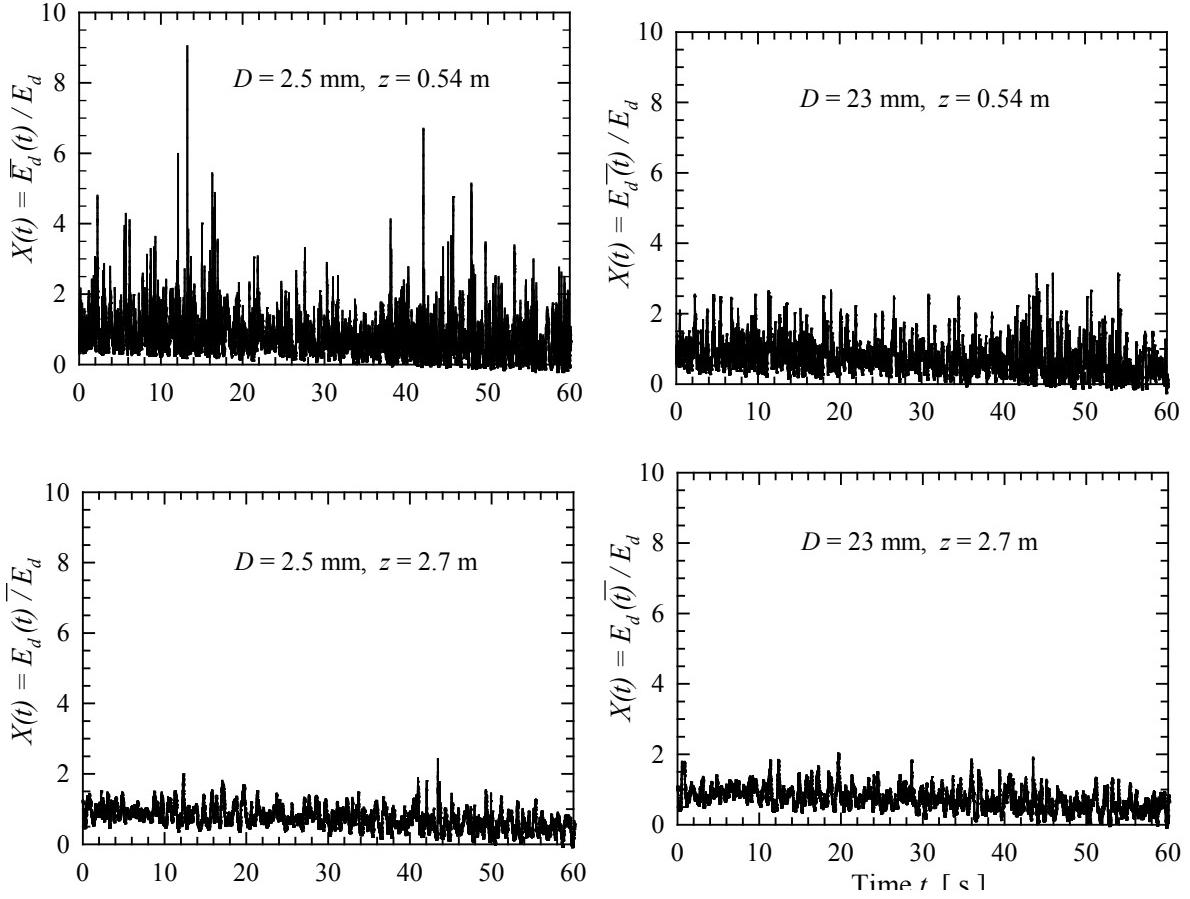
## **PUBLICATIONS**

Darecki, M., D. Stramski, and M. Sokolski, Measurements of high-frequency light fluctuations induced by sea surface waves with an Underwater Porcupine Radiometer System, *J. Geophys. Res.*, doi:10.1029/2011JC007338, in press.

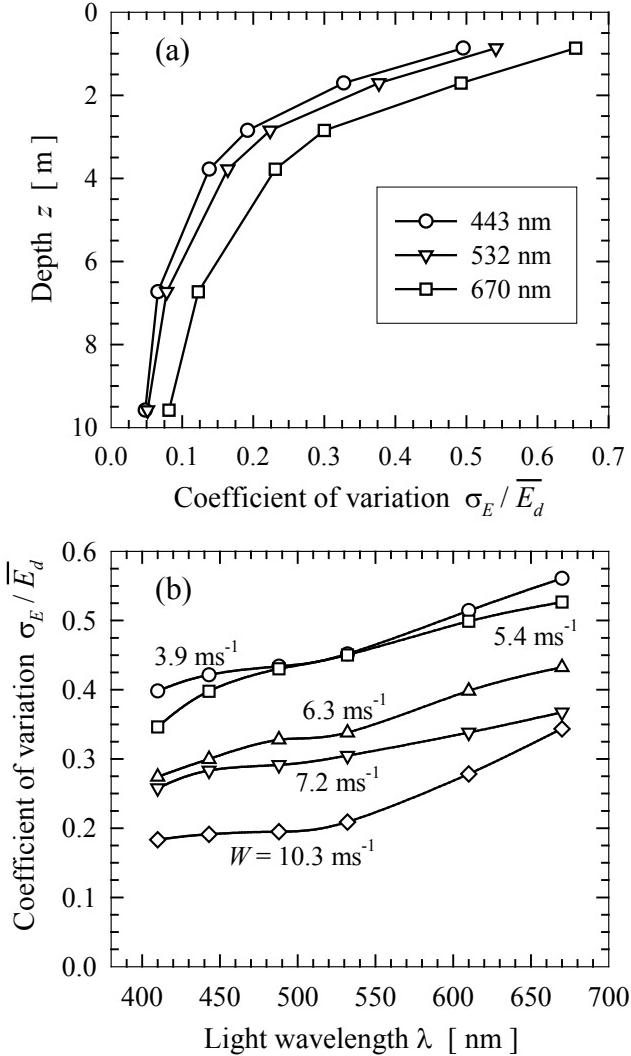
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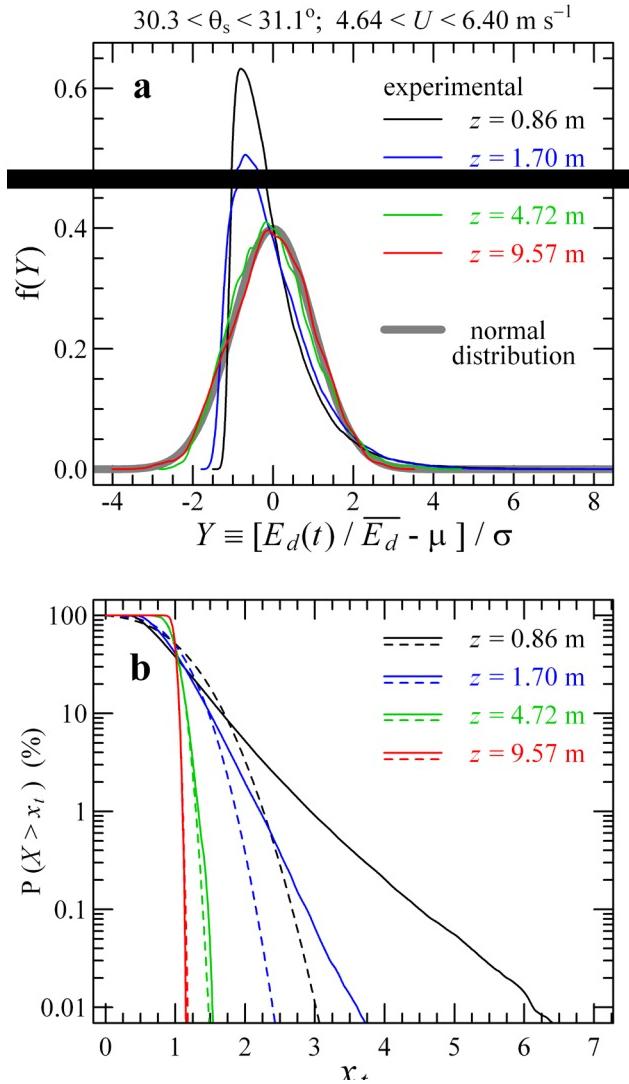
*Figure 1. An Underwater Porcupine Radiometer System with its major components indicated. The presented configuration of the instrument consists of six irradiance sensors, each with different size of plane cosine collector (from 2.5 mm to 23 mm), and seventeen radiance sensors for observations at different zenith angles within two orthogonal azimuthal planes. Note that the configuration of the sensors used routinely during the RaDyO experiments in the Santa Barbara Channel and off Hawaii Islands was different than that shown in this figure. For example, seven irradiance sensors, each equipped with the same size of collector (2.5 mm) but different spectral filters, were used during the RaDyO experiments.*



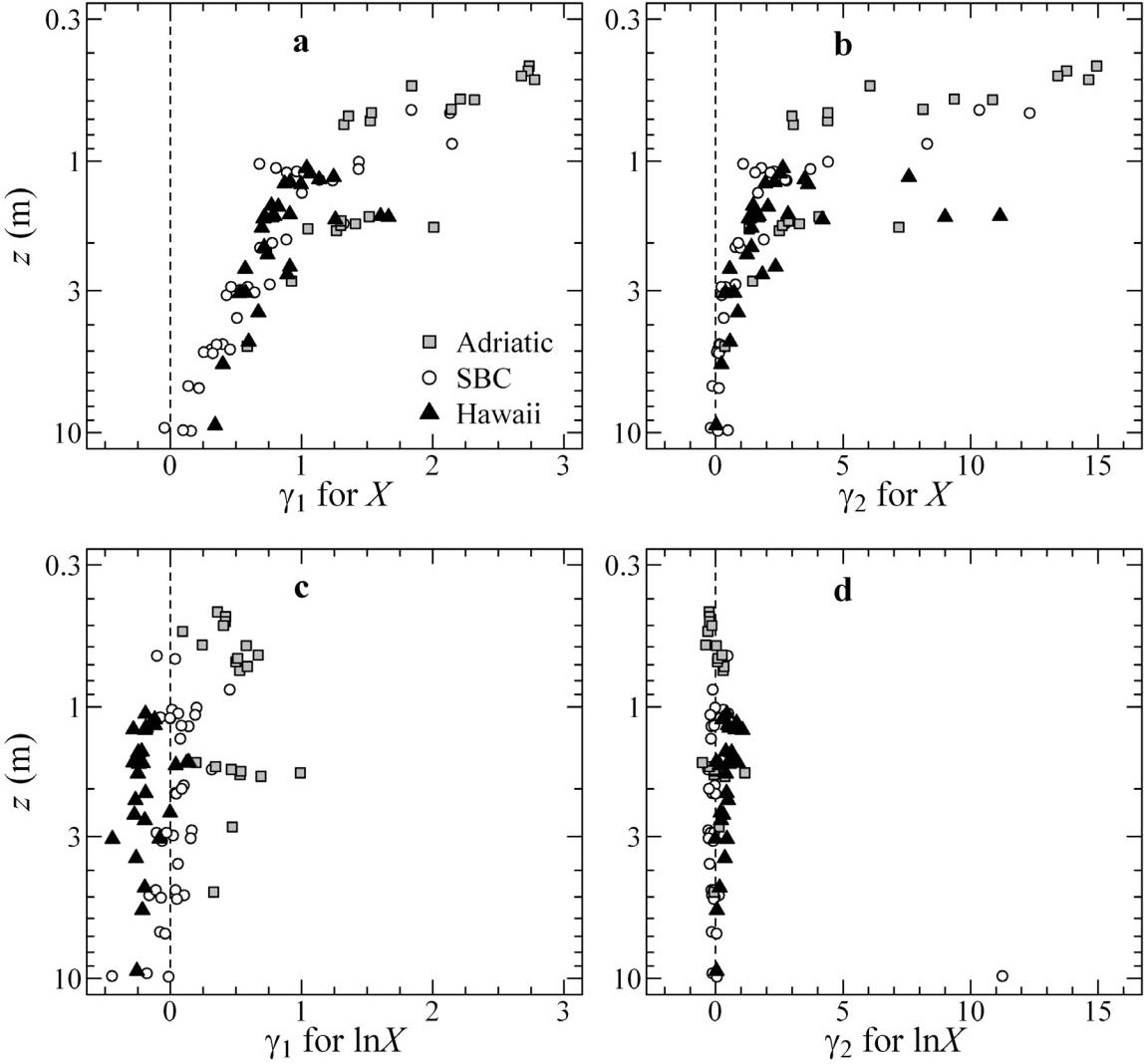
**Figure 2.** Example fluctuations in downwelling irradiance measured at two depths,  $z = 0.54 \text{ m}$  and  $2.7 \text{ m}$ , with the Porcupine irradiance sensors equipped with the interference filter centered at 532 nm and cosine collectors having a diameter  $D$  of 2.5 mm and 23 mm as indicated. The time-series data are shown for the normalized irradiance,  $X(t) = E_d(t) / \bar{E}_d$ . The measurements were made in the Adriatic Sea on June 12, 2009 at 9:44 am and 9:58 am local time under clear skies, wind speed  $U = 2.7 \text{ m s}^{-1}$ , solar zenith angle  $\theta_s = 35^\circ - 37^\circ$ , and the beam attenuation coefficient of seawater at 555 nm,  $c(555) = 0.33 \text{ m}^{-1}$ .



**Figure 3.** (a) The depth dependence of the coefficient of variation of the downwelling irradiance at three light wavelengths (443, 532, and 670 nm) based on measurements made in the Santa Barbara Channel on September 11, 2008 between 11:35 am and 12:56 pm local time under sunny conditions, solar zenith angle  $\theta_s = 30^\circ - 33^\circ$ , wind speed  $W = 4.1 - 6.4 \text{ m s}^{-1}$ , and the beam attenuation coefficient of seawater at 555 nm,  $c(555) = 0.68 \text{ m}^{-1}$ . (b) Spectral dependence of the coefficient of variation of downwelling irradiance measured at near-surface depths under sunny conditions and different wind-wave conditions as indicated by the wind speed  $W$ . The measurements were made in the Santa Barbara Channel on the following 5 days in 2008: September 15 (2:15 pm local time,  $W = 10.3 \text{ m s}^{-1}$ ), Sept. 16 (1:55 pm,  $W = 6.3 \text{ m s}^{-1}$ ), Sept. 18 (09:48 am,  $W = 5.4 \text{ m s}^{-1}$ ), Sept. 19 (1:41 pm,  $W = 7.2 \text{ m s}^{-1}$ ), and Sept. 20 (09:42 am,  $W = 3.9 \text{ m s}^{-1}$ ) under sunny conditions, depth  $z = 0.91 - 1.25 \text{ m}$ , solar zenith angle  $\theta_s = 42^\circ - 46^\circ$ , and the beam attenuation coefficient of seawater at 555 nm,  $c(555) = 0.54 - 0.78 \text{ m}^{-1}$ .



**Figure 4. (a)** Probability density function,  $f(Y)$ , of the standardized downwelling irradiance,  $Y \equiv [E_d(t) / \bar{E}_d - \mu] / \sigma$ , based on example measurements performed in the Santa Barbara Channel on September 11, 2009 within a period of 1.5 hours, during which the solar zenith angle  $\theta_s$  varied from about  $30.3^\circ$  to  $33.1^\circ$  and the wind speed  $U$  from  $4.6 \text{ m s}^{-1}$  to  $6.4 \text{ m s}^{-1}$ . The parameters  $\mu$  and  $\sigma$  represent the mean and standard deviation of the normalized downwelling irradiance,  $X \equiv E_d(t) / \bar{E}_d$ . The experimental probability density functions are shown as colored lines for four different depths as indicated. For comparison, the theoretical probability density function of a normal distribution is shown as grey line. **(b)** Complementary cumulative distribution functions,  $P(X > x_t)$ , of the normalized downwelling irradiance,  $X \equiv E_d(t) / \bar{E}_d$ , are shown as solid lines for the same example measurements as in panel (a). For comparison, the dashed lines show the complementary cumulative distribution functions,  $P(X > x_t)$ , corresponding to the theoretical normal distribution. The values of  $x_t$  represent specific threshold values of  $X$ , for which the probability of the complementary cumulative distribution function is determined.



**Figure 5.** (a) The skewness coefficient,  $\gamma_1$ , of the normalized downwelling irradiance,  $X \equiv E_d(t)/\bar{E}_d$ , as a function of depth for 21 measurements made in the Adriatic Sea (grey squares), 36 measurements from the Santa Barbara Channel (open circles), and 29 measurements from the Hawaii experiment (black triangles). The solar zenith angle for this entire data set consisting of 86 measurements varies between  $14.4^\circ$  and  $39.9^\circ$ , and the wind speed between  $1.3 \text{ m s}^{-1}$  and  $11.1 \text{ m s}^{-1}$ . The dashed vertical line at  $\gamma_1 = 0$  indicates the skewness corresponding to a symmetrical distribution, such as a normal distribution. (b) Same as panel (a) but for the coefficient of excess kurtosis  $\gamma_2$ . (c) Same as panel (a) but the coefficient of skewness was calculated for the log-transformed normalized downwelling irradiance,  $\ln X \equiv \ln[E_d(t)/\bar{E}_d]$  rather than the normalized irradiance  $X$ . (d) Same as panel (b) but the coefficient of excess kurtosis was calculated for the log-transformed normalized downwelling irradiance,  $\ln X \equiv \ln[E_d(t)/\bar{E}_d]$ .